(hep-ph/yymmxxx)
HU-SEFT R 1994-19

PHENOMENOLOGICAL IMPLICATIONS OF SUPERSYMMETRY IN LEFT-RIGHT ELECTROWEAK MODEL*

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ABSTRACT

The basics of a supersymmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model are reviewed. The production and subsequent decays of the doubly charged triplet higgsino $\tilde{\Delta}^{\pm\pm}$ in the Next Linear Collider are discussed. The slepton pair production in the framework of this model is also analysed.

1. Introduction

Despite of the success of the Standard Model (SM) there are still unsolved problems in particle physics which motivate searches for more fundamental theories. One of the most appealing extensions of the SM is the left-right symmetric model based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [1]. Among many attractive features of this model is its capability to explain the lightness of the ordinary neutrinos via so called see-saw mechanism [2] which occurs naturally due to the dynamical treatment of both left and right handed fields. Indeed, the anomalies measured in the solar [3] and atmospheric [4] neutrino fluxes as well as the COBE observation [5] of the existence of the hot component of dark matter seem to indicate that neutrinos could have a small non-vanishing mass. Another peculiar feature of the model is the existence of lepton number violating interactions, partly due to the massive Majorana neutrinos and partly because of doubly charged components of triplet Higgs fields which carry lepton number two.

On the other hand the left-right symmetric model similarly to the SM suffers from the hierarchy problem: the masses of the Higgs scalars diverge quadratically. As in the SM, supersymmetry can be used to cure this problem.

*Talk given by Martti Raidal in "The First Arctic Workshop on Future Physics and Accelerators," Saariselkä, Finland August 21-26, 1994.

Here we shall consider a minimal susy left-right model where the number of Higgs fields is the smallest possible [6]. In particular we shall discuss how one can test the model in future collider experiments. Since the doubly charged triplet higgsinos give the most distinctive experimental signature we shall study the triplet higgsino production in possible e^-e^-, e^+e^-, $e^-\gamma$ and $\gamma\gamma$ options of the Next Linear Collider (NLC) [7]. If the doubly charged higgsino is too heavy to be produced in the NLC we shall study how its extra contribution as a virtual intermediate state would affect the selectron production in e^+e^- collisions.

2. A supersymmetric left-right model

The minimal set of Higgs fields in the non-susy left-right model consists of a bidoublet ϕ_u and a $SU(2)_R$ triplet Δ. In supersymmetrization, the cancellation of chiral anomalies among the fermionic partners of the triplet Higgs fields Δ requires introduction of the second triplet δ with opposite $U(1)_{B-L}$ quantum number. Due to the conservation of the $B-L$ symmetry δ does not couple to leptons and quarks. In order to avoid a trivial Kobayashi-Maskawa matrix for quarks, also another bidoublet ϕ_d should be added to the model. This is because supersymmetry forbids a Yukawa coupling where the bidoublet appears as a conjugate.

We have chosen the vacuum expectation values for the Higgses, which break the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ into the $U(1)_{em}$, to be as follows

$$< \phi_u >= \begin{pmatrix} \kappa_u & 0 \\ 0 & 0 \end{pmatrix}, < \phi_d >= \begin{pmatrix} 0 & 0 \\ 0 & \kappa_d \end{pmatrix}, < \Delta >= \begin{pmatrix} 0 & 0 \\ v & 0 \end{pmatrix}, < \delta >\equiv 0. \quad (1)$$

Here $\kappa_{u,d}$ are of the order of the electroweak scale 10^2 GeV. The vev v of the triplet Higgs has to be much larger in order to have the masses of the new gauge bosons W_2 and Z_2 sufficiently high [8]. With the choice (1) of the vev's the charged gauge bosons do not mix and W_L corresponds to the observed particle.

We assume the superpotential to have the following form:

$$\begin{aligned} W &= h_u^Q \widehat{Q}_L^{cT} \widehat{\phi}_u \widehat{Q}_R + h_d^Q \widehat{Q}_L^{cT} \widehat{\phi}_d \widehat{Q}_R \\ &+ h_u^L \widehat{L}_L^{cT} \widehat{\phi}_u \widehat{L}_R + h_d^L \widehat{L}_L^{cT} \widehat{\phi}_d \widehat{L}_R + h_\Delta \widehat{L}_R^T i\tau_2 \widehat{\Delta} \widehat{L}_R \\ &+ \mu_1 \mathrm{Tr}(\tau_2 \widehat{\phi}_u^T \tau_2 \widehat{\phi}_d) + \mu_2 \mathrm{Tr}(\widehat{\Delta}\widehat{\delta}). \end{aligned} \quad (2)$$

Here $\widehat{Q}_{L(R)}$ stands for the doublet of left(right)-handed quark superfields, $\widehat{L}_{L(R)}$ stands for the doublet of left(right)-handed lepton superfields, $\widehat{\phi}_u$ and $\widehat{\phi}_d$ are the two bidoublet Higgs superfields, and $\widehat{\Delta}$ and $\widehat{\delta}$ the two triplet Higgs superfields.

In the superpotential (2) the R-parity, $R = (-1)^{3(B-L)+2S}$, is preserved. This ensures that the susy partners with $R = -1$ are produced in pairs and that the lightest supersymmetric particle (LSP) is stable. In order to preserve the naturalness of the theory the supersymmetric mass parameters μ_i should be close to the scale of the soft supersymmetry breaking[9]. We assume here that the parameters $|\mu_i|$ are of the order of the weak scale.

Figure 1: Branching ratios of (a) the left slepton and (b) the right slepton as functions of the slepton mass for μ_2 =300GeV.

We are especially interested in the doubly charged fermions occurring in the Higgs triplet superfields. Their mass matrix is particularly simple, since doubly charged higgsinos do not mix with gauginos. The triplet higgsinos, like the triplet Higgses, carry lepton number two and therefore the final state of their decay must also have even lepton number in the case of R-parity conservation.

There are five charginos $\psi_j^{\pm}$ and nine neutralinos ψ_i^0 in this model. The physical particles $\tilde{\chi}_i^{\pm}$ and $\tilde{\chi}_i^0$ are found by diagonalization of the mass Lagrangian:

$$\tilde{\chi}_i^{\pm} = \sum_j C_{ij}^{\pm} \psi_j^{\pm}, \tag{3}$$

$$\tilde{\chi}_i^0 = \sum_j N_{ij} \psi_j^0. \tag{4}$$

The masses of the particles depend on the following parameters: the soft gaugino masses, the supersymmetric Higgs masses μ_1 and μ_2, the vacuum expectation values κ_u, κ_d, and v, and the gauge coupling constants. We have calculated numerically the composition of neutralinos and charginos for different values of the parameters. The neutralinos are Majorana particles, whereas the charginos combine together to form Dirac fermions. For our numerical calculations we have always taken $g_R = g_L = 0.65$, $h_\Delta = 0.3$, $\mu_1 = 200\,\mathrm{GeV}$ and $m_{W_R} = 500\,\mathrm{GeV}$. The parameter μ_2 is equal to the doubly charged higgsino mass M_Δ. In the following we shall consider two different sets of the model parameters. In the first case the soft gaugino masses are taken to be 1 TeV (LRM I) and in the second case 200 GeV (LRM II). For the larger soft gaugino masses the neutralinos are predominantly higgsinos whereas for the smaller soft masses they are mainly gauginos.

The mixing of the left and right selectrons is assumed to be negligible and their masses $m_{\tilde{e}L}$ and $m_{\tilde{e}R}$ are taken to be equal.

Figure 2: Feynman diagrams for the pair production of the doubly charged higgsinos in electron-positron collisions.

3. Tests of the model in the NLC

The allowed decay modes of the triplet higgsinos are

$$\begin{aligned} \tilde{\Delta}^{++} &\rightarrow \Delta^{++}\,\lambda^0,\ \Delta^+\,\lambda^+, \\ & \quad\ \tilde{\Delta}^+\,W_2^+,\ \tilde{l}^+ l^+. \end{aligned} \tag{5}$$

In large regions of the parameter space, the kinematically favoured decay mode is $\tilde{\Delta}^{++} \rightarrow \tilde{l}^+ l^+$. As the masses of Δ and W_2 are of the order of the SU$(2)_R$ breaking scale v [10], the first three decay channels are kinematically forbidden in our case of the relatively light triplet higgsinos. In the following we shall assume that $\tilde{\Delta}^{++}$ decay in 100% into the $\tilde{l}l$ final state.

The charged sleptons $\tilde{l}$ can decay as follows:

$$\tilde{l}^+ \rightarrow l^+ + \tilde{\chi}_i^0, \tag{6}$$

$$\tilde{l}^+ \rightarrow \nu + \tilde{\chi}_i^+, \tag{7}$$

$$\tilde{l}^+ \rightarrow W^+ + \tilde{\nu}. \tag{8}$$

The decay mode (8) is kinematically disfavoured and we do not consider it. The decay of the the right-slepton into the neutrino channel will in general be kinematically disfavoured because of the heaviness of the right-handed neutrino. In Fig. 1 the branching ratios of the different channels are plotted as the function of the left-slepton and right-slepton masses. For the left-slepton decay the channel (7) becomes dominant immediately when the slepton mass exceeds the mass of the lightest chargino. The chargino has several decay channels, e.g. into a lepton-slepton pair, a W-chargino pair, and a quark-squark pair.

The NLC will, besides the usual e^+e^- option, be able to work also in e^-e^-, $e^-\gamma$ and $\gamma\gamma$ collision modes. In these collisions the doubly charged higgsinos $\tilde{\Delta}^{\pm\pm}$ can be produced through the following processes:

$$e^+e^- \rightarrow \tilde{\Delta}^{++}\tilde{\Delta}^{--}, \tag{9}$$

Figure 3: Total cross section for the reaction $e^+e^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$ as a function of the higgsino mass $M_{\tilde{\Delta}}$ for two values of selectron mass $m_{\tilde{l}}$ at the collision energy 1TeV.

$$e^-e^- \to \tilde{\chi}^0\tilde{\Delta}^{--}, \tag{10}$$

$$\gamma e^- \to \tilde{l}^+\tilde{\Delta}^{--}, \tag{11}$$

$$\gamma\gamma \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}. \tag{12}$$

We have chosen these reactions for investigation because they all have a clean experimental signature: a few hard leptons and missing energy. Futhermore, they all have very small background from other processes. The fact that $\tilde{\Delta}^{\pm\pm}$ carries two units of electric charge and two units of lepton number and that it does not couple to quarks makes the processes (9) - (12) most suitable and distinctive tests of the susy left-right model.

Reaction $e^+e^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$

The triplet higgsino pair production in e^+e^- collision occurs through the diagrams presented in Fig. 2. In contrast with the triplet Higgs fields whose mass is in the TeV scale [10], the mass of the triplet higgsino is given by the susy mass parameter μ_2, which is a free parameter. As we mentioned before, for the reason of naturality its value should not differ too much from the electroweak breaking scale, i.e. $\mu_2 = O(10^2\,\mathrm{GeV})$.

In Fig. 3 the total cross section for the process (9) is presented as a function of the mass of $\tilde{\Delta}^{--}$ for the collision energy of $\sqrt{s} = 1$ TeV and for two values of the selectron mass, $m_{\tilde{l}} = 200$ GeV and 400 GeV. As can be seen, the cross section for these parameter values is about 0.5 pb and it is quite constant up to the threshold region. To have an estimate for the event rate, one has to multiply the cross section with the branching ratio of the decay channel of the produced higgsinos used for the search. As pointed out earlier, the favoured decay channel may be

$$\tilde{\Delta}^{--} \to \tilde{l}^-l^- \to l^-l^-\tilde{\chi}^0. \tag{13}$$

Figure 4: Feynman diagrams for the production of the doubly charged higgsino in electron-electron collisions.

Figure 5: Total cross section for the reaction $e^-e^- \to \tilde{\chi}^0\tilde{\Delta}^{--}$ as a function of the higgsino mass $m_{\tilde{\Delta}}$ for two values of selectron mass $m_{\tilde{l}}$ at the collision energy 1TeV.

Here l can be any of e, μ and τ with practically equal probabilities. The signature of the pair production reaction (9) would be the purely leptonic final state associated with missing energy. In the SM a final state consisting of four charged leptons and missing energy can result from cascade decays. In the susy left-right model there are, however, some unique final states not possible in the SM, namely those with non-vanishing separate lepton numbers.

Reaction $e^-e^- \to \tilde{\chi}^0\tilde{\Delta}^{--}$

The production of the triplet higgsino $\tilde{\Delta}^{--}$ in electron–electron collision occurs via a selectron exchange in t-channel (see Fig. 4). In Fig. 5 the cross section is presented as a function of $M_{\tilde{\Delta}^{--}}$ for two values of the selectron mass, $m_{\tilde{e}} = 200$ GeV and 500 GeV, at the collision energy $\sqrt{s} = 1$ TeV. It is taken into account that the final state neutralino mass is related to the triplet higgsino mass as they both depend on the parameter μ_2. The signature of the reaction is a same-sign lepton pair created in the cascade decay (13) of $\tilde{\Delta}^{--}$, associated with the invisible energy carried by neutralinos. The two leptons need not be of the same flavour since the $|\Delta L| = 2$

Figure 6: Feynman diagrams for the photoproduction of the doubly charged higgsino.

Figure 7: Total cross section for the reaction $\gamma e^- \to \tilde{l}^+ \tilde{\Delta}^{--}$ as a function of the higgsino mass $m_{\tilde{\Delta}}$ for two values of selectron mass $m_{\tilde{l}}$ at the electron electron (positron) collision energy 1TeV.

Yukawa couplings are not necessarily diagonal. This may be useful for distinguishing the process from the selectron pair production $e^- e^- \to \tilde{e}^- \tilde{e}^- \to e^- e^- +$ neutralinos, which is the leading process for the selectron production in the susy version of the Standard Model. In the SM the final states $e^- \mu^-$, $e^- \tau^-$ and $\mu^- \tau^-$ are forbidden.

Reaction $\gamma e^- \to \tilde{l}^+ \tilde{\Delta}^{--}$

The mechanism of producing high-energy photon beams by back-scattering high intensity laser pulses off the high energy electron beams proposed by Ginzburg et al.[11] allows the NLC to operate also as a photon collider. There are three Feynman diagrams contributing to the photoproduction reaction (11): electron exchange in s-channel, selectron exchange in t-channel and triplet higgsino exchange in t-channel (see Fig. 6). In Fig. 7 the total cross section is presented as a function of the triplet higgsino mass for the electron-electron center of mass energy $\sqrt{s_{ee}} = 1$ TeV. The cross section is determined by convoluting the photon energy distribution $P(y)$, i.e. $\sigma(s_{ee}) = \int dy P(y) \sigma(s_{e\gamma})$.

The experimental signature of the reaction is three lepton final state associated

Figure 8: Feynman diagrams for the production of the doubly charged higgsinos in photon-photon collisions.

with missing energy. The positive lepton is any lepton, and the two negative ones can be any combination of the electron, muon and tau, provided the triplet higgsino coupling is not diagonal. A suitable choice of the final state will cut down the SM background coming e.g. from the reaction $e^-\gamma \to e^- Z^*$. The cross section is above O(100 fm) for a large range of the masses $M_{\tilde{\Delta}^{--}}$ and $m_{\tilde{e}}$, providing hence a good potential for the discovery of $\tilde{\Delta}^{--}$.

Reaction $\gamma\gamma \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$

This reaction is an alternative of, but not competitative with, the reaction (9) for producing a doubly charged higgsino pair. Feynman diagram of the process is presented in Fig. 8. Because the photon energies are not monochromatic but broadly distributed, no sharp threshold will be visible in the production cross section. Moreover, the maximum collision energy will be some 20% less than the e^+e^- energy. On the other hand, the only unknown parameter in the process is the mass $M_{\tilde{\Delta}^{--}}$ as the couplings are completely determined by the known electric charge of the higgsino. The cross section of the reaction as a function of $M_{\tilde{\Delta}^{--}}$ is given in Fig. 9 for the collision energy $\sqrt{s_{ee}}= 1$ TeV. The experimental signature of the reaction will be of course the same as for the process (9), i.e. four charged leptons associated with missing energy. The cross section is large because of the photon coupling to electric charge.

Slepton pair production

If the doubly charged higgsinos turn out to be too heavy to be produced in the NLC one can study their possible contributions as the intermediate virtual particles to the production of lighter susy particles. One such process is the slepton pair production (see Fig. 10)

$$e^+e^- \to \tilde{l}^+\tilde{l}'^-, \tag{14}$$

where $\tilde{l},\ \tilde{l}' = \tilde{e}, \tilde{\mu}, \tilde{\tau}$. Experimentally, the slepton pair production is possibly one of the first susy processes to be seen since sleptons are supposed to be relatively light among the superpartners of the ordinary particles. Compared with the MSSM there

Figure 9: Total cross section for the reaction $\gamma\gamma \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$ as a function of the higgsino mass $m_{\tilde{\Delta}}$ at the electron electron collision energy 1TeV.

Figure 10: Feynman diagrams for the slepton pair production in electron positron collisions.

is one extra s-channel diagram involving the heavy neutral gauge boson Z_2, five extra t-channel diagrams due to the larger number of neutralinos and one new u-channel diagram in our model.

In Fig. 11 we present the total cross section of the selectron pair production as a function of the selectron mass $m_{\tilde{e}}$ for a fixed triplet higgsino mass $M_{\tilde{\Delta}}$. Fig. 11a corresponds to the situation at LEP200 with $\sqrt{s} = 200$ GeV (here $M_{\tilde{\Delta}} = 110$ GeV) and Fig. 11b at a linear collider with $\sqrt{s} = 1$ TeV ($M_{\tilde{\Delta}} = 300$ GeV).

The cross sections in the two left-right symmetric model cases differ slightly because in LRM I the t-channel processes are supressed since the higgsino couplings are small, in LRM II there is no such suppression. For comparison we have plotted in Fig. 11 also the corresponding cross section in the MSSM I (II). As one can see, the cross sections in the susy left-right model are systematically appreciably larger than in the MSSM. This is due to two factors, firstly the number of gauginos is larger and secondly the triplet higgsino contribution is large, though dependent on the unknown triplet higgsino coupling to the electron and selectron.

The most intriguing difference between the susy left-right model and the MSSM

Figure 11: The total cross section $\sigma(e^+e^- \to \tilde{e}_L^+\tilde{e}_L^-) + \sigma(e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-) + 2\sigma(e^+e^- \to \tilde{e}_L^+\tilde{e}_R^-)$ as a function of the selectron mass $m_{\tilde{l}}$ (a) for the collision energy $\sqrt{s} = 200$ GeV and triplet higgsino mass $M_{\tilde{\Delta}} = 110$ GeV, (b) for $\sqrt{s} = 1$ TeV, $M_{\tilde{\Delta}} = 300$ GeV. LRM I (II) refer to two supersymmetric left-right models and MSSM I (II) to two versions of the minimal supersymmetric Standard Model described in the text.

with respect to the slepton pair production is the existence of the u-channel process of Fig. 10c. This reaction occurs only for a right-handed electron and a left-handed positron, whereas in the s- and t-channel processes all chirality combinations may enter. Use of polarized beams could therefore give us more information of the triplet higgsino contribution. Assuming that the decay mode $\tilde{e} \to e\tilde{\chi}_1^0$ is dominant, we present in Fig. 12 the angular distribution of the final state electron e^- in the case the electron is right-handedly and positron left-handedly polarized (P_{+-}) and in the opposite case (P_{-+}) for $\sqrt{s} = 1$ TeV, $m_{\tilde{e}} = M_{\tilde{\Delta}} = 300$ GeV. In model LRM I (Fig. 12a) the t-channel contributions are suppressed since the light neutralinos are mainly consisting of the higgsinos. The distribution P_{+-} is larger and it is slightly peaked in the backward direction because of the u-channel contribution. In model LRM II (Fig. 12b) both t-channel (forward peak) and u-channel (backward peak) contributions are observable. The latter is absent in the MSSM, of course.

In the MSSM with the unification assumption the right-selectron is lighter than the left-selectron [12]. If only $\tilde{e}_R$'s are produced, the difference between the MSSM and the supersymmetric left-right model would be especially large and observable in the NLC.

4. Conclusions

Phenomenologically the most intriguing prediction of the supersymmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model is the existence of doubly charged higgsino $\tilde{\Delta}^{++}$. It carries two units of lepton number and it has a clear decay signature: two same sign leptons, which are not necessarily the same type, and the missing energy. The production

Figure 12: The angular distribution of the final state electron in the cascade process $e^+e^- \to \tilde{e}^+\tilde{e}^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ for $\sqrt{s} = 1$ TeV, $M_{\tilde{\Delta}} = m_{\tilde{e}} = 300$ GeV in the model (a) LRM I, (b) LRM II. P_{+-} corresponds to the case where the incoming electron has positive and the incoming positron has negative longitudinal polarization, and P_{-+} corresponds to the opposite case.

cross sections of $\tilde{\Delta}^{++}$ in e^+e^-, e^-e^-, $e^-\gamma$ and $\gamma\gamma$ collision modes of the NLC are at the level of pb. Its contribution to the slepton pair production processes should be observable in angular distributions of the process.

Acknowledgements

The work has been supported by the Finnish Academy of Science. One of the authors (M.R.) expresses his gratitude to the Viro-säätiö, Emil Aaltosen Säätiö and Wihurin Rahasto foundations for grants.

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